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Evaluation on the efficiency of wastewater treatment plants with data envelopment analysis from a water-energy nexus perspective

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ABSTRACT

With the urgent demand on the optimization from both aspects of water quality and energy consumption, the efficiency of WWTPs from a water-energy nexus perspective appears to be increasingly important. In this study, the energy efficiency of 210 WWTPs in Yangtze River Delta of China were assessed through data envelopment analysis (DEA). The operational conditions of DEA were polished through a hierarchical framework. All WWTPs were classified into 4 categories of anaerobic-anoxic-oxic (AAO), anaerobic-oxic (AO), oxidation ditch (OD) and sequencing batch reactor (SBR). And the variables derived from the indicators were revised through production possibility set (PPS) in order to remove the ratio form. The results showed that WWTPs in Yangtze River Delta had a high efficiency overall. It also indicated that advanced treatment process didn't have a remarkable impact on the efficiency. Moreover, there were much room for the optimization on pollutant removal in terms of the ideal discharge limit converted from the projection.

Keywords: wastewater treatment plants, water-energy nexus, data envelopment analysis, production possibility set, technical process, discharge standard

NONMENCLATURE

Abbreviations	
WWTP	Wastewater Treatment Plant
DEA	Data Envelopment Analysis
DMU	Decision Making Unit
VRS	Variable Returns to Scale
PPS	Production Possibility Set
COD	Chemical Oxygen Demand
BOD_5	5-day Biochemical Oxygen Demand
NH_4^+-N	Ammonia-Nitrogen
TN	Total Nitrogen
TP	Total Phosphorus
AAO	Anaerobic-Anoxic-Oxic
AO	Anaerobic-Oxic
OD	Oxidation Ditch
SBR	Sequencing Batch Reactor
MSBR	Modified Sequencing Batch Reactor
CAST	Cyclic Activated Sludge Technology
CASS	Cyclic Activated Sludge System
Symbols	
yr	year
%	ratio

1. INTRODUCTION

The efficiency of wastewater treatment plants (WWTPs) reflects the sustainability. While indicators are taken as the input and output variables, WWTPs can be taken as decision making units (DMUs) assessed by data envelopment analysis (DEA) [1]. So far, many researchers have evaluated the efficiency by DEA from an integrated perspective. Jiang et al. [2] evaluated the sustainability with indicators involving energy, water quality, economy and labor. Dong et al. [3] measured the eco-efficiency from aspects of energy, water quality and economy. Hu et al. [4] assessed the eco-efficiency of WWTPs with variables of energy, water quality, investment and capacity loading rate.

Although results are comprehensive with much factors considered, WWTPs mainly function with energy consumption and water quality improvement which are two major aspects for the optimization of WWTPs [1]. As the treatment process consumes large quantity of energy to improve water quality [5, 6], WWTPs are energy-intensive facilities [7, 8] so that it is meaningful to evaluate the energy efficiency.

Therefore, this paper focused on efficiency that characterizes the energy converting to pollutants removal. A hierarchical framework was also established to polish the operational conditions of DEA. Then, we calculated the improvement potential from the aspect of stricter discharge limits.

2. MATERIAL AND METHODS

2.1 Research scope

The scope selected is Yangtze River Delta which generally consists of Shanghai, Jiangsu, Zhejiang and Anhui (Fig. 1). It is the most prosperous region in China with large amount of wastewater discharge and high intense of energy usage. Nowadays, the integrated regional development of Yangtze River Delta boosts strategic significance in China's further development. Thus, the selection of this scope is under the background of national macro development strategy.

Fig. 1 Research scope of Yangtze River Delta in China.

In addition, considering the avoidance of disturbance from external factors such as economy, society, climate, etc., the WWTPs within the scope is good for establishing indicators with high correspondence between energy consumption and pollutant removal.

2.2 Data source

The data of WWTPs was extracted from Urban Drainage Yearbook published by China Urban Water Association, which records data information on yearly operation situation of WWTPs in China in 2015.

In order to ensure the accuracy, the data cleaning was fully implemented. With the primary screening condition of region, we got 263 WWTPs within the scope. Then, we screened out the data with incomplete information. As a result, 251 valid samples of WWTPs were put into use in this study.

2.3 DEA with revised operational condition

DEA is a benchmark methodology used to assess the sustainability of DMUs by projection to the frontier convexity [9]. In this study, it was crucial to evaluate the efficiency score and figure out the projection of WWTPs with variable returns to scale (VRS). Thus, output-oriented DEA VRS model [10] was selected. Moreover, a hierarchical framework was developed to orderly polish DEA's operational conditions at levels of DMU, indicator and variable (Fig. 2).

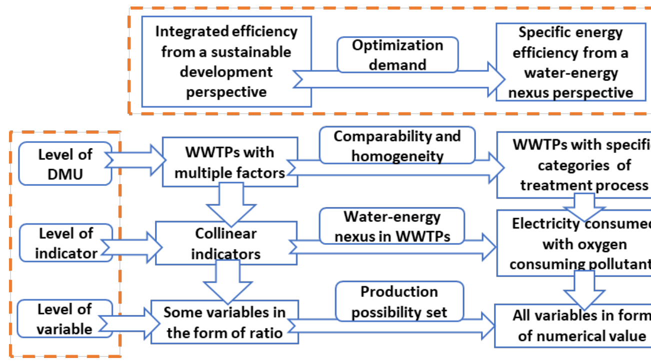

Fig. 2 A hierarchical framework for polish on operational conditions of DEA.

2.3.1 Level of DMU

To establish a set of DMUs with comparability and homogeneity, we did the classification according to the

Table 1 Categories and number of WWTPs with advanced treatment process.

Type of processes	Number of WWTPs	Number of WWTPs with advanced treatment process
AAO	90	12
AO	17	7
OD	75	17
SBR	28	6
Others	17	n/a
Combined process	24	n/a
Total	251	42

*The category of AAO contains the process named University of Cape Town, while the category of SBR contains UNITANK, MSBR, CAST and CASS as well.

*The categories of others and combined process didn't meet the demand of comparability and homogeneity so that they weren't be evaluated and the number of WWTPs with advanced treatment process wasn't counted, either.

Table 2 Average statistics of variables for each category.

	AAO	AO	OD	SBR
Input Variables				
Annual electricity consumption (kWh)	7,463,112	16,818,215	5,030,506	5,075,451
Total BOD_5 in influent (ton)	3,257	7,627	1,845	2,515
Total NH_4^+-N in influent (ton)	707	1,609	410	500
Output Variables				
Annual BOD_5 removed (ton)	3,072	7,309	1,714	2,400
Annual NH_4^+-N removed (ton)	655	1,455	381	470

type of technical process recorded in the yearbook, like anaerobic-anoxic-oxic (AAO), anaerobic-oxic (AO), oxidation ditch (OD), sequencing batch reactor (SBR) and others. After induction and integration, many processes with small amount were deleted and there were 210 WWTPs retained in this study. Furthermore, 4 categories of AAO, AO, OD and SBR formed as a result and the number of WWTPs with advanced treatment process were also counted in Table 1.

2.3.2 Level of indicator

In terms of water-energy nexus, we consider the indicators that characterize well water and energy in WWTPs. As electricity takes up the majority of the total energy, annual electricity consumption was chosen.

However, with electricity selected, not all pollutants could be on behalf of water quality. Considering that procedure of bio-decomposition consumes oxygen continuously transported by aerators of which the energy consumption takes up 45-75% in total of WWTPs [1, 11], the removal of BOD_5 and NH_4^+-N were chosen.

2.3.3 Level of variable

To avoid the convexity problem that DEA models may bring about [12], this paper used the method of PPS to revise variables that are in form of ratio.

As the rule goes that numerator and denominators of the output-ratio variables should be taken as additional output and input variables respectively [13], the revised variables are shown in Fig. 3.

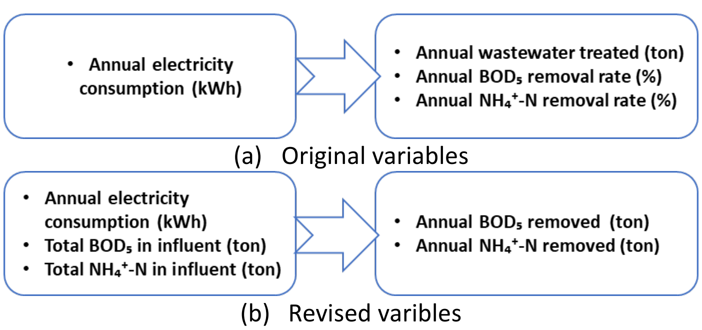

Fig. 3 Variables revision based on PPS.

3. RESULTS AND DISSCUSION

3.1 Characteristics of DMUs

The descriptive results of the WWTPs were listed in Table 2. With the increase in energy consumed, the removal of BOD_5 and NH_4^+-N rose up at the same time. AO consumed the most electricity of 1.68×10^7 kWh averagely, while OD took up the least with 5.03×10^6 kWh. Correspondingly, from the aspect of water quality, AO still ranked the first with 7,309 ton BOD_5 and 1,455 ton NH_4^+-N removed, while OD ranked the last with 1,714 ton BOD_5 and 381 ton NH_4^+-N removed.

3.2 Efficiency analysis of DMUs

Table 3 listed the results of efficiency scores of WWTPs in 4 categories. AO was the type owning the highest average efficiency score of 0.9767, while SBR possessed the best efficient rate of 64.29%.

Table 3 Comparison of efficiency of WWTPs of each category.

	AAO	AO	OD	SBR
Number of total WWTPs	90	17	75	28
Number of efficient WWTPs	27	10	31	18
%Efficient WWTPs	30.00	58.82	41.33	64.29
Average efficiency score	0.9767	0.9845	0.9708	0.9826

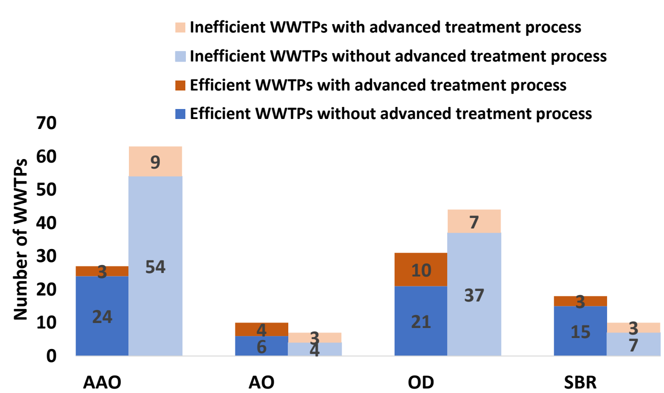

Fig. 4 Number of the efficiency and inefficiency WWTPs with advanced treatment process.

Table 4 Average projection and improvement ratio of each category.

	BOD_5 removal			NH_4^+-N removal		
	Origin (ton)	Projection (ton)	Improvement ratio (%)	Origin (ton)	Projection (ton)	Improvement ratio (%)
AAO	1,639	1,709	4.27	339	354	4.48
AO	7,309	7,344	0.48	1,455	1,461	0.43
OD	1,650	1,716	4.00	375	383	2.13
SBR	2,401	2,440	1.62	470	477	1.55

Besides, there were 27, 10, 31 and 18 WWTPs got full efficiency score in each category. In terms of efficient rate, SBR ranked first with a ratio value of 64.29% while AAO was the last with a low efficient rate of 30%. That means the WWTPs in AAO category had the most room for improvement. The average efficiency score of 4 categories are closed to 1, which means all WWTPs possessed a high performance overall. Although some WWTPs emerged to be the benchmark, the score of the others were relatively low and there didn't exist a huge gap between efficient and inefficient WWTPs

In addition, not all WWTPs with advanced treatment process showed high efficiency. As shown in Fig. 4, there were only 3, 4, 10 and 3 out of 12, 7, 17 and 6 WWTPs came out to be the benchmark among AAO, AO, OD and SBR category respectively. Thus, it can be concluded that advanced treatment process didn't impress a remarkable effect on energy efficiency. Theoretically, though advanced treatment process costed more energy, the water quality was also improved. Meanwhile, the advanced treatment processes were mostly designed to further remove the TP and TN, while the indicators in this study were about BOD_5 and NH_4^+-N. Therefore, advanced treatment process in this study didn't show great impact on the energy efficiency.

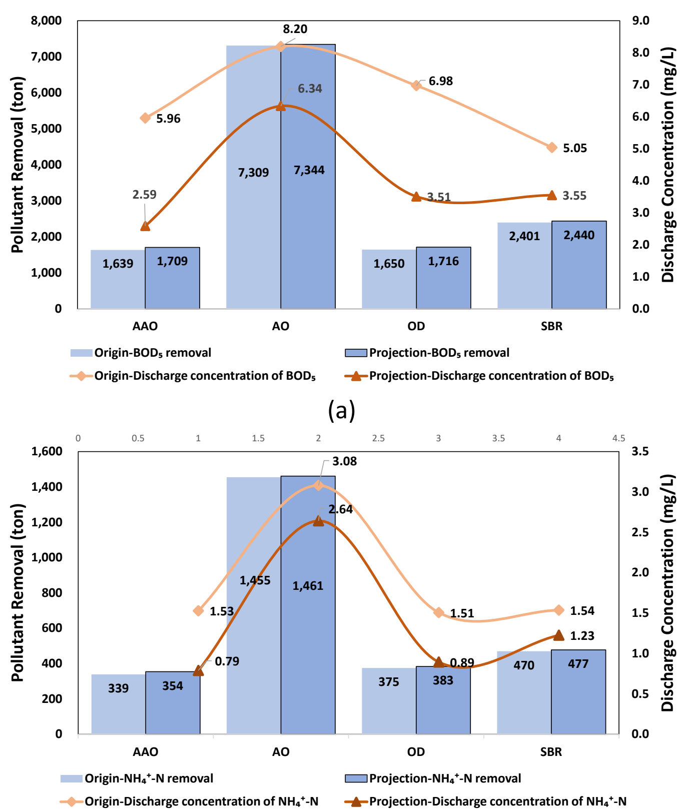

Fig. 5 Projection of annual pollutants removal and ideal discharge limit of (a) BOD_5 and (b) NH_4^+-N.

3.3 Improvement analysis of inefficient WWTPs

When some WWTPs got the full efficiency score, the others were inefficient and there existed room to improve. The projection solved by DEA indicates the potential for inefficient DMUs. In this study, the projection was about how much BOD_5 and NH_4^+-N should be removed to reach the efficient level.

Table 4 listed the average projection of inefficient WWTPs with the current input unchanged. Although improvement ratios of all categories were small, the next breakthrough would be difficult to overcome in terms of

Table 5 Comparison of ideal discharge limit with current standard in Yangtze River Delta.

Discharge standard		BOD_5 (mg/L)	NH_4^+-N (mg/L)
GB 18918-2002 *Class IA*		10	5
DB 31/199-2018 *Class IA*		10	1.5
DB 32/1072-2007		-	5
DB 33/2169-2018		10	1.5
Ideal limits of discharge	AAO	2.59	0.79
	AO	6.34	2.64
	OD	3.51	0.89
	SBR	3.55	1.23

*GB 18918-2002 represents Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant; DB 31/199-2018 represents Integrated Wastewater Discharge Standard; DB 32/1072-2007 represents Discharge Standard of Main Water Pollutants for Municipal Wastewater Treatment Plant & Key Industries of Taihu Area; DB 33/2169-2018 represents Discharge Standard of Major Water Pollutants for Municipal Wastewater Treatment Plant.

*The discharge limit of BOD_5 wasn't involved in DB 32/1072-2007.

the ideal discharge limits of BOD_5 and NH_4^+-N figured out in Fig. 5.

There were 3 province-level (DB 31/199-2018, DB 32/1072-2007, DB 33/2169-2018) and 1 nation-level standards (GB 18918-2002) involved in Table 5. Comparing to the standards in Table 5, the ideal limit of BOD_5 was lower than 10 mg/L, the limit in current standards. And the ideal limits of NH_4^+-N of 3 categories are lower than 1.5 mg/L. This indicates that each category of WWTPs had much potential to improve the efficiency in terms of discharge limits.

4. CONCLUSIONS

In this study, evaluation on the energy efficiency of WWTPs was implemented. Through polishing the operational conditions of DEA, the efficiency score showed that WWTPs in Yangtze River Delta owned an overall high efficiency. Besides, the impact of advanced treatment process on energy efficiency was not remarkable. Moreover, there were much room for improvement in terms of stricter discharge limits.

Although this paper focused on water-energy nexus in WWTPs, some internal factors were neglected, such as capacity, loading rate, influent concentration, etc. In addition, the polish on operational conditions can't fully solve the shortcoming of DEA, because DEA can only assess the relative efficiency among a set of DMUs. The absolute efficiency of the WWTPs should be predicted in a more comprehensive and objective way. And the methodology such as life cycle assessment would also be helpful. Therefore, the optimization strategy should be predicted and analyzed from a more comprehensive perspective including multiple scenarios. Thus, more related internal indicators should be considered with other methodology together used in further studies.

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